

ANALYSIS OF CADMIUM-CADMIUM COULOMETERS USED FOR CHARGE CONTROL IN NICKEL-CADMIUM SPACE BATTERIES

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ABSTRACT

This paper reports the results of two years of coulometer work at the Goddard Space Flight Center. Coulometers have been designed, developed, and shown to be acceptable for controlling the charging of Nickel-Cadmium spacecraft batteries. Two coulometer manufacturers have demonstrated a capability to construct and deliver operational units that are space qualified and tested to flight specifications. The incorporation of this device in the space battery control system reduces the rate of overcharging; it produces a voltage signal when the battery charge has been restored so the charge can be interrupted or reduced, and thus eliminates the heat dissipation which would result from unnecessary overcharging. This improves the voltage characteristics and lengthens the life of the battery.

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INTRODUCTION

The coulometer, by implication, is a device that measures coulombs. The cadmium-cadmium alkaline cell has come to be called a "coulometer" because of the application for which it was designed. The coulomb is defined in terms of ampere-seconds. The coulometer would therefore measure ampere-seconds. The cadmium-cadmium coulometer responds to ampere-seconds, yielding a signal after a specific quantity has passed through the device. The battery engineer is attuned to thinking of ampere-seconds generally in terms of ampere-hours, a much larger unit; therefore this report will confine its usage to the latter.

The electrochemical coulometer is not a new device. It has a long and varied history in commercial applications. The innate design of the nickel-cadmium space cell resulted in voltage characteristics making it virtually impossible to design a charge control system that is entirely acceptable to the engineer or scientist concerned. The coulometer is a simple alkaline cell using the identical parts and general construction features that are used in the manufacture of the nickel-cadmium space cell. Due to this relationship, both the coulometer and the space cell yield comparable lifetime performance characteristics. Earlier efforts by other agencies to make a coulometer of this type for space applications embodied much the same concept and thinking. The Goddard design is believed to be the first successful design of a cadmium-cadmium space coulometer. It is unique in the type of separators specified, the techniques of forming, and in the amount of electrolyte used.

PREDICTED ELECTRODE POTENTIALS

In 1963 Goddard scientists began to investigate the feasibility of building functional alkaline electrochemical space coulometers. Predicted electrode potentials were constructed using individual electrode measurements made in nickel-cadmium space cells with reference electrodes. (See Figure 1.) The nickel-nickel coulometer voltage pattern is shown in the upper portion, while the cadmium-cadmium one is shown in the lower part. The coulometer cell voltages can be read as differences in potential between the pairs of curves

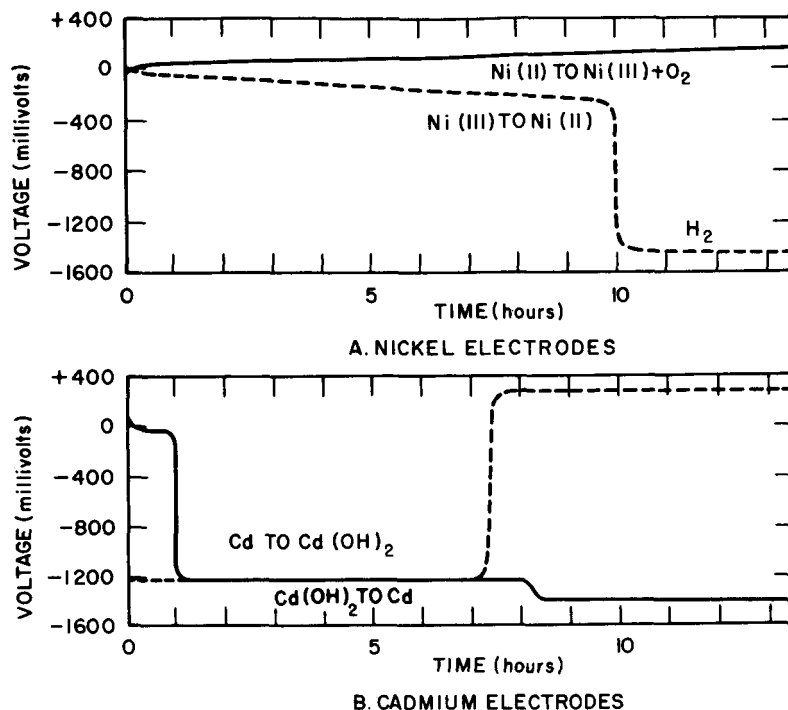


Figure 1—Predicted Electrode Potentials for Electrochemical Integrators

depicted. These differences were used as basic criteria in the testing and evaluation of the Goddard made coulometers—and they are found to be very close to precise.

DESIGN AND CONSTRUCTION

*SAFT-type six-ampere-hour nickel and cadmium electrode stacks were procured along with non-woven nylon having a 20-25 mil thickness. All of these parts were currently being flown in nickel-cadmium alkaline space batteries. The plate thicknesses were about 30 mils. The nickel-nickel and the cadmium-cadmium coulometers were assembled using two positive and two negative electrode stacks per coulometer. The cells were sealed in polystyrene experimental cases fitted with pressure gauges which were evacuated and sealed after forming. (See Figures 2 and 3.) The electrolyte was added in larger measure so that one may prefer to call this a wet cell as against the usual "damp" term

*SAFT is a French battery manufacturer of considerable note in the manufacture of sealed nickel-cadmium batteries who has licensed General Electric and Gulton Industries to manufacture SAFT type batteries in this country.

applied to the conventional nickel-cadmium space cell. "Flooding" the cell with electrolyte is made possible since gas recombination functions are not necessary in normal coulometer operations.

FORMING

The forming process is graphically described in Figure 4. A current of magnitude $C/10$, where C = rated capacity of the electrode stack, is passed through the vented cell. Starting at point A in figure 4 at the instant of commencement of the forming cycle, one finds that the voltage rises directly to an oxygen generating plateau described electrically as approximately 1.45 volts. In five to seven hours the voltage rises to the hydrogen generation plateau, approximately

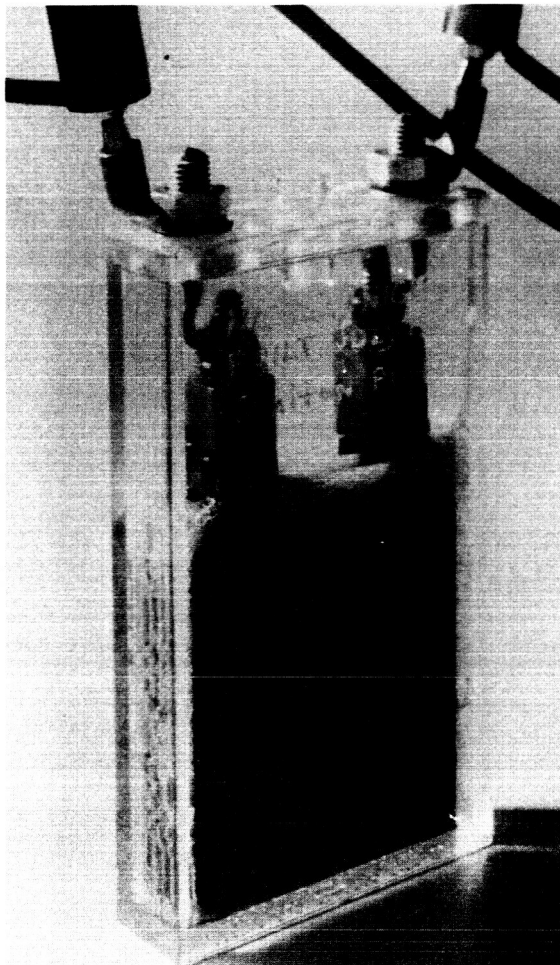


Figure 2—An Experimental Nickel-Nickel Coulometer

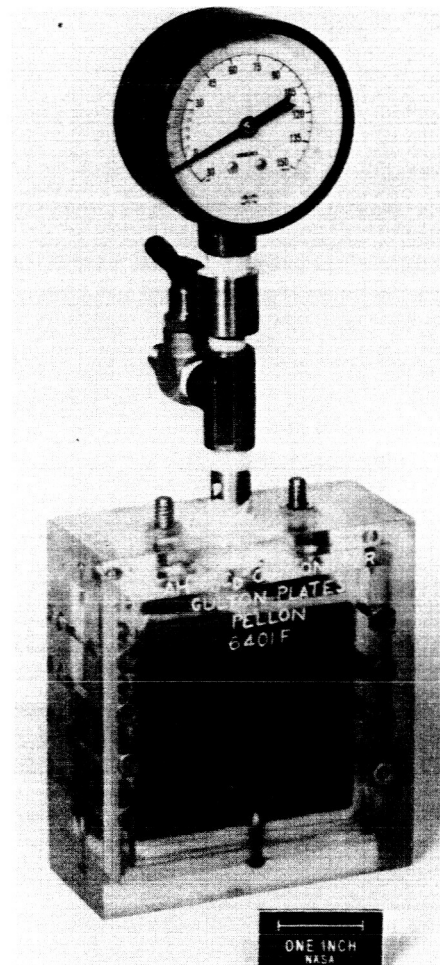


Figure 3—An experimental Cadmium-Cadmium Coulometer

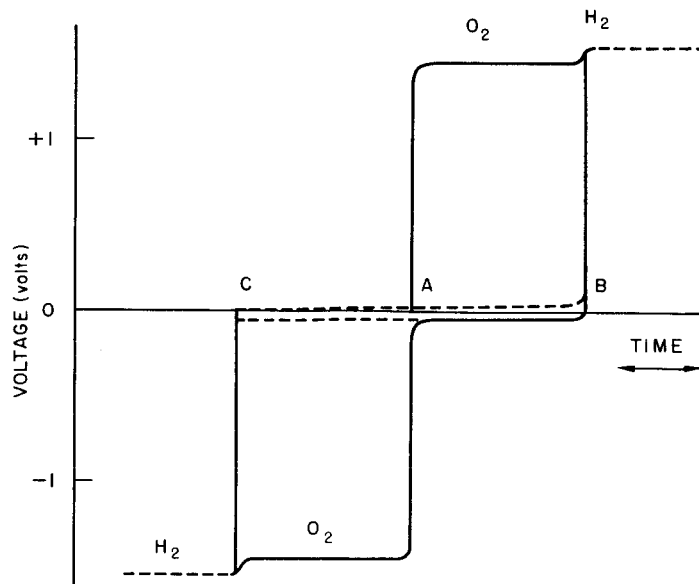


Figure 4—Forming Cycle for a Cadmium-Cadmium Coulometer

1.55 volts. As soon as the hydrogen plateau is reached, the forming current is reversed through the cell and the voltage falls to point B where it continues to point A, requiring four to five hours. It then falls directly from point A to the opposite oxygen generation plateau at -1.45 volts where it remains for four to five hours, finally reaching the hydrogen plateau and returning to point C upon interruption of the current, at which time the formation cycle is complete. At this point in time the traces of residual oxygen are pumped out and the cell is sealed and ready for use.

One may be academically curious as to the amount of capacity which might be gained by remaining on the hydrogen plateaus. Investigation of this possibility was concluded with negative results.

ACCELERATED TESTING

Goddard made five cadmium-cadmium coulometers and five nickel-nickel coulometers using electrode stacks of the six ampere-hour size. In order to establish life capability in the minimum possible time, an accelerated testing program was devised. It consisted of passing a rather large current of 10 amperes through the coulometer and reversing the direction when the terminal voltage rose to 1.0 volt. This is roughly depicted by the graph in Figure 5. In this manner it was possible to obtain the full cell capacity in about 40 minutes, resulting in an output of 36 half cycles per day. Figure 6 illustrates the results

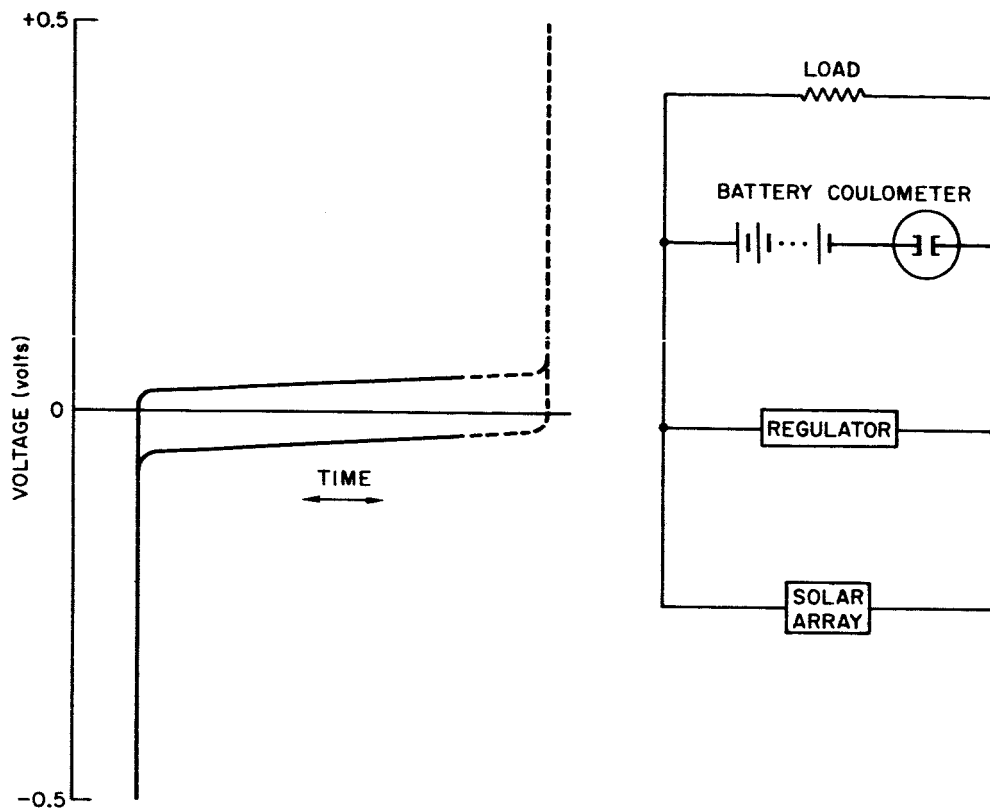


Figure 5-The Cadmium-Cadmium Coulometer Behavior

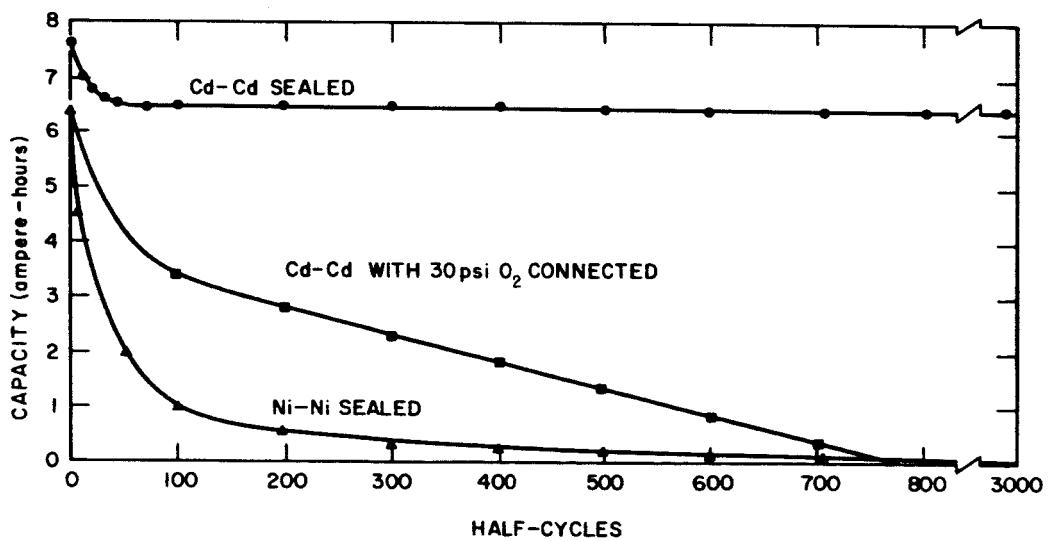


Figure 6-Coulometer Studies (6 AH plates - 10 ampere rate)

obtained in such testing*. The nickel-nickel coulometer proved not worthy of mention. The cadmium-cadmium device plateaus out very conveniently within 100 half-cycles, and this has been used as basic criteria for qualifying cells for flight purposes. Gas analyses were conducted to verify the forming parameters. The effect of oxygen illustrated in Figure 6 where a cadmium-cadmium cell is operated with 30 psi of pure oxygen connected. It follows that this coulometer must be hermetically sealed from oxygen environs.

LEAKAGE

The amount of current (in milliamperes) leaking through the coulometer was measured as a function of the magnitude of the terminal signal in millivolts. This is illustrated in Figure 7. Six-ampere-hour space-battery-industry-manufactured cells were used as test samples. (See Figure 8.) The terminal voltage was held for five minutes at 100 millivolt increments from 100 to 1500 millivolt values and the milliampere rate recorded at the end of each period. It was noted that the leakage rate continued to decrease in magnitude long after the five

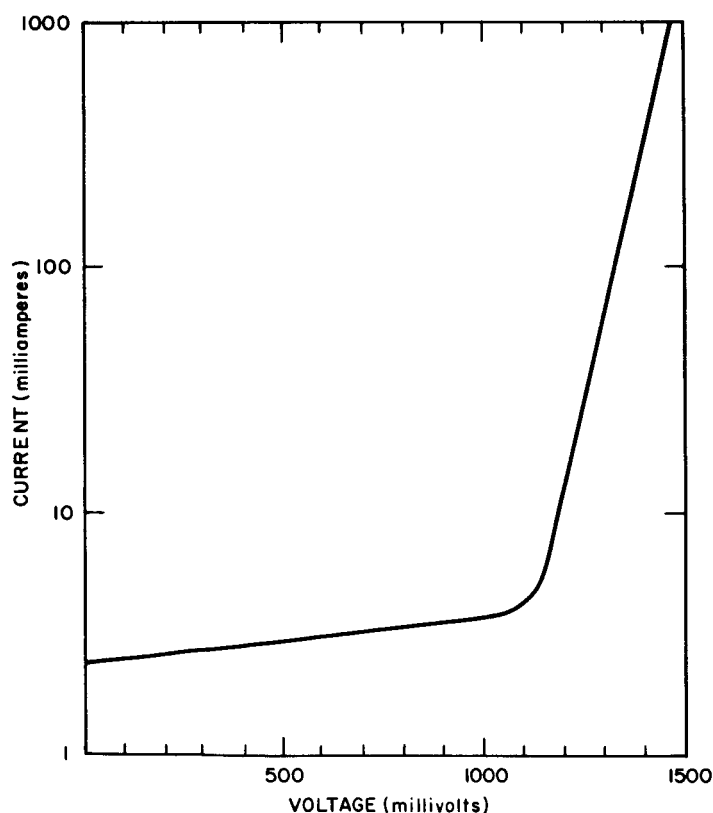


Figure 7—Coulometer Leakage Rate
(6 AH cell Nov. 65)

*One "half-cycle" is described by a single passage between points "B" and "C" on the dotted line shown in Figure 2.

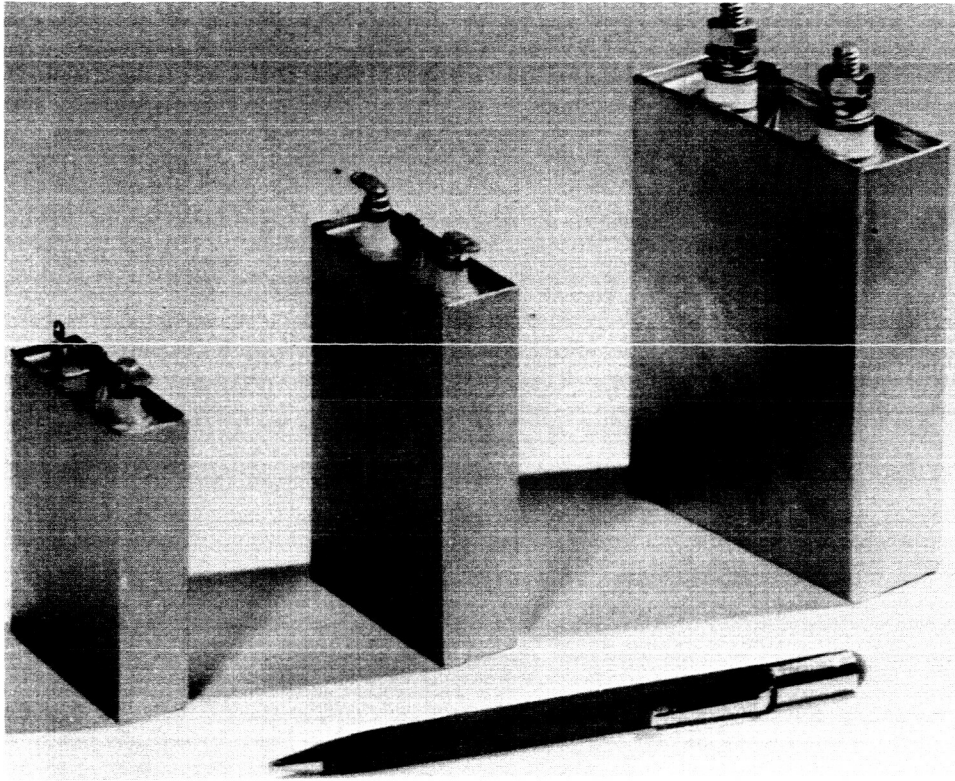


Figure 8—Cadmium-Cadmium Coulometers Designed and Manufactured for Space Applications

minute period has expired. It is generally concluded that the leakage rate is negligible for most applications being smaller than $C/1000$ where the signal voltage is chosen at 1000 millivolts or less.

THE SIGNAL

The term "signal" refers to the sharp rise in terminal voltage when the coulometer's electrodes become polarized in the manner illustrated in Figure 1. The useful characteristic behavior to be applied in space-battery-charge control is indicated by the dotted portion of Figure 5. This latter figure applies, in general, to the design of the Radio Astronomy Explorer (RAE) Satellite Program.

The signal voltage may be selected by the instrumenter. If he chooses to operate with a signal of 600 - 800 millivolts he may find it convenient to employ a silicon diode junction to prevent the coulometer from rising above that level. If he chooses to operate within a lower voltage range, he may wish to use the lower forward-breakdown voltage of the germanium diode junction.

IMPEDANCE

The internal resistance of the six-ampere-hour coulometer is no more than that of the nickel-cadmium space cell. In fact, optimally designed by using an abundance of electrolyte to insure coverage of the electrodes, the coulometer resistance should be lower. Goddard personnel have obtained measurements indicating less than ten milliohms for the properly made cell.

ELECTROLYTE

The level of electrolyte should be above the plates for optimum performance. There are no gassing problems to contend with in the properly designed and instrumented cadmium-cadmium coulometer. This capability was demonstrated with flooded cells using 1000 millivolt signal limits and 5C current rates.

SEPARATORS

Since the cadmium-cadmium coulometer can be operated in the flooded state the thickness of the separators may not be too critical. Experiments with up to 25 mils plate separation, accomplished with several layers of non-woven nylon, revealed negligible increases in cell impedance in flooded cells. The dry thickness of the thickest separator material used in nickel-cadmium space cells is believed to be about 30 mils. The plate separation attained by this latter material is slightly more than 5 mils. In view of these facts and to obtain the optimum in life performance, it is recommended that over 20 mils of dry separator material be used. Cells made with 10 mil non-woven-nylon have been procured and operated with space batteries to 40°C on 90 minute orbital regimens for periods in excess of one year. However, there is little penalty in using the thicker separator and there is the possibility of increased life and certainly increased reliability.

APPLICATION

There are two philosophies of application illustrated schematically in Figures 9 and 10. In both cases the coulometer is placed in series with the battery so that all discharge current will pass through the coulometer. These circuit designs permit 99 per cent of the charge current to pass through the coulometer; the point of interruption is occasioned by the coulometer terminal voltage rise which is used as a signal to "switch" to the trickle charge mode of

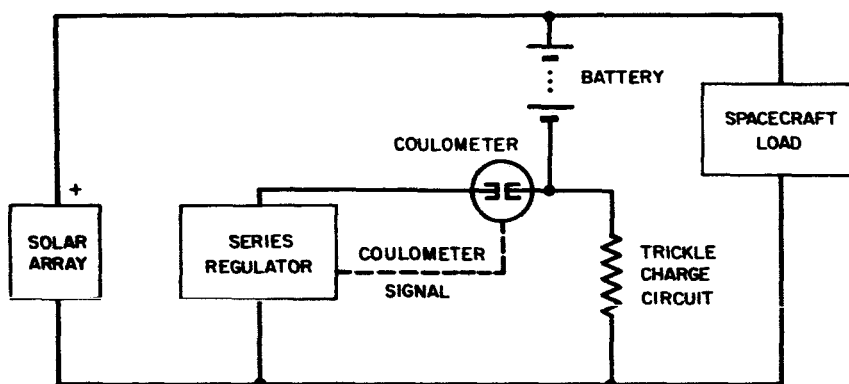


Figure 9-Block Diagram Showing Coulometer Installation With a Series Regulator

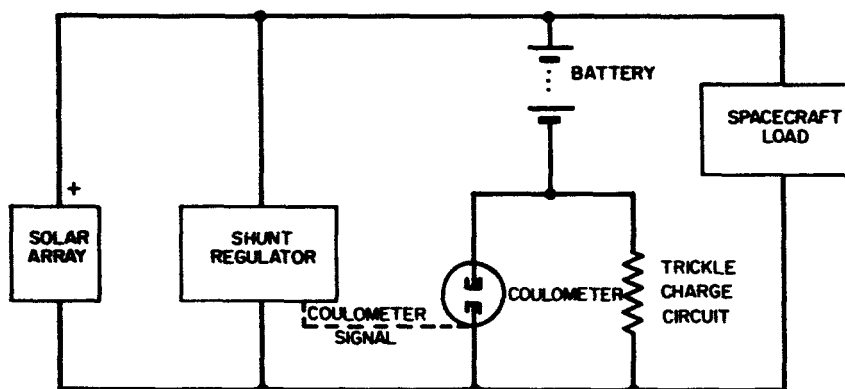


Figure 10-Block Diagram Showing Coulometer Installation With a Shunt Regulator

operation. In Figure 9 this action is accomplished by switching the coulometer out of the circuit with the series regulator. In Figure 10 the shunt regulator adjusts the system voltage to the battery charge voltage necessary to maintain the appropriate trickle charge rate (perhaps $C/30$). The shunt type of control is used in the Radio Astronomy Explorer program because it reduces the number of components between the battery and the system, thereby reducing total power requirements.

A typical twelve-cell battery showing arrangement of 11 nickel-cadmium cells plus a coulometer is illustrated in Figures 11 and 12. The measurements and notations apply to a six-ampere-hour battery as planned for the RAE satellite.

265q/CELL
7.05 LBS/12 CELLS
3 LBS FOR PACKAGING
100 IN.³ SIZE

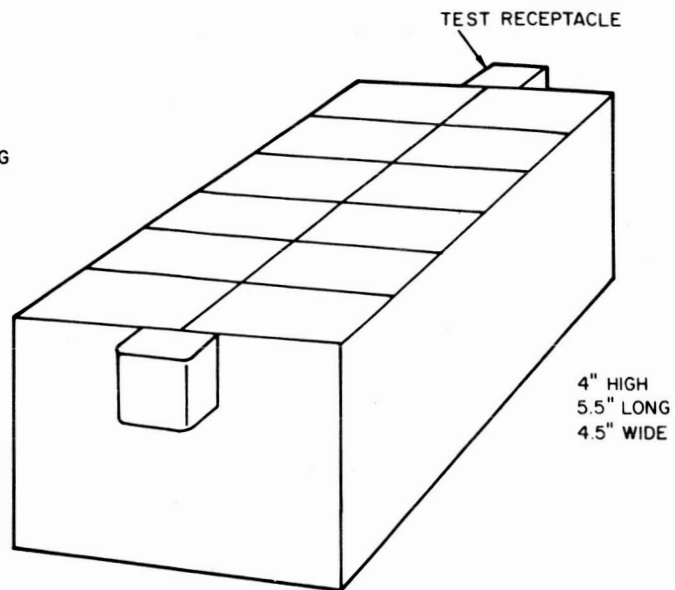


Figure 11-Cell Assembly-Battery

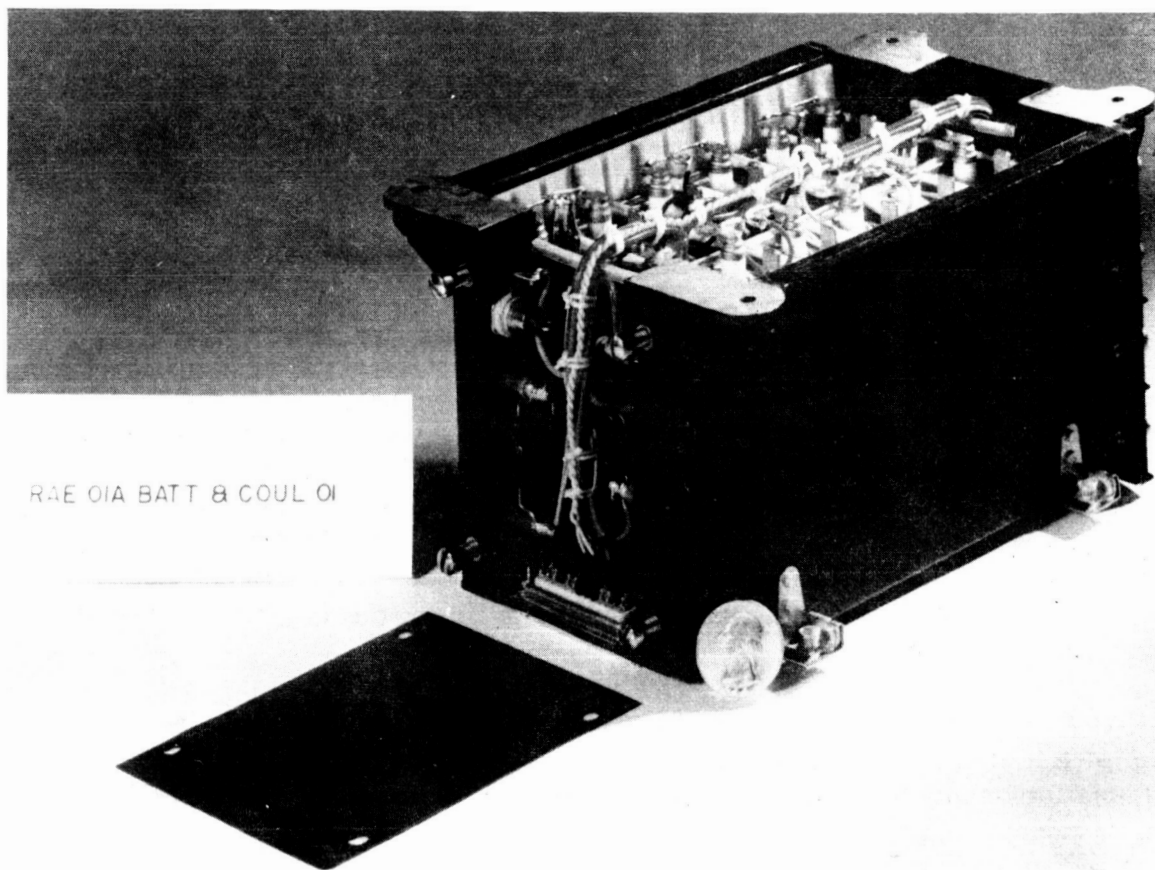


Figure 12-The Goddard-Designed RAE Prototype Battery

SYSTEMS TESTS

RAE requirements (17% depth of discharge) were used to determine the behavior of the cadmium-cadmium coulometer in the control function of a space power system. Twelve-cell batteries (one a coulometer) were constructed and cycled on an accelerated regimen employing the maximum depth of discharge repeatedly without change from cycle to cycle. The results of tests at 0°C, 25°C, and 40°C are illustrated in Figures 13, 14, and 15. It may be noted that the coulometer signal appears when 99% of the charge has been restored thus preventing the voltage from climbing into dangerous gassing modes. The internal nickel-cadmium cell pressures, as indicated in the figures, remain well below one atmosphere at all temperatures. The null voltage of the coulometer is negligible (less than 50 millivolts). Over 1.5 years of testing in these constraints have proven that these systems are acceptable for missions in excess of one year duration.

CONCLUSION

The cadmium-cadmium coulometer is recommended for one year missions having a 20% depth of discharge within normal space battery operating temperatures. It must be pointed out that the voluminous test data acquired at NAD

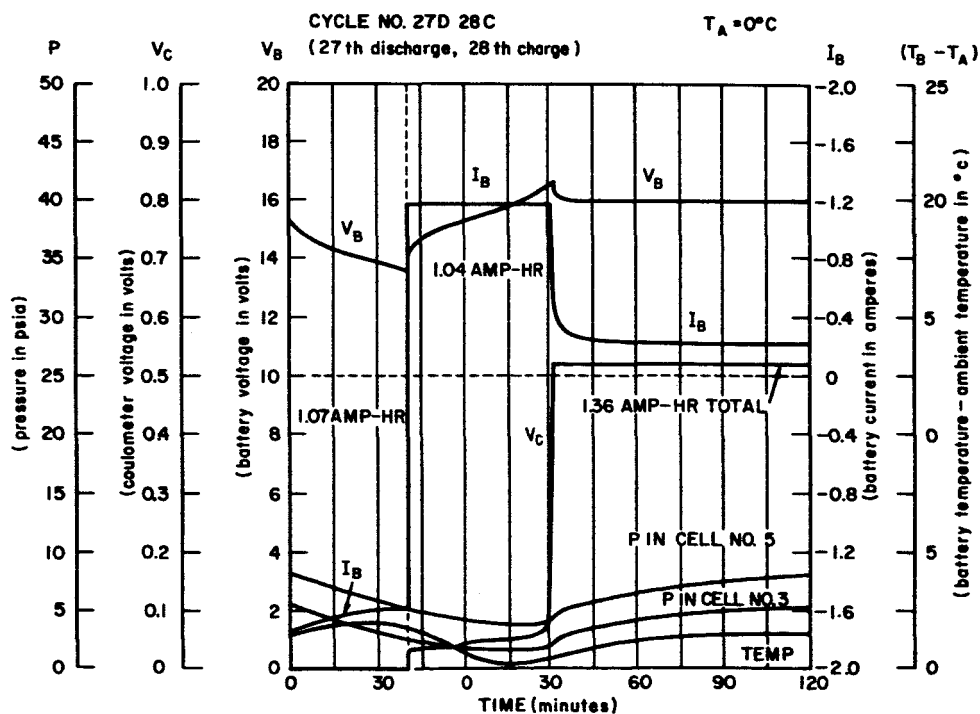


Figure 13—RAE Battery Test No. T2/CLM/101(0), Cycle No. 27D 28C
(27th discharge, 28th charge)

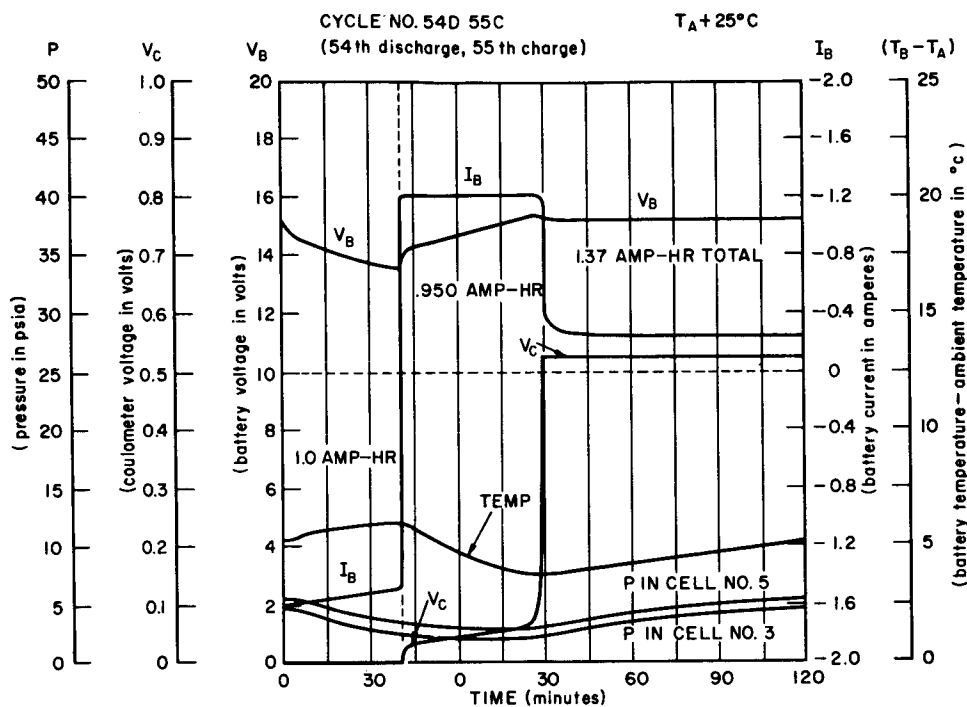


Figure 14—RAE Battery Test No. 101 + 25, Cycle No. 54D 55C
(54th discharge, 55th charge)

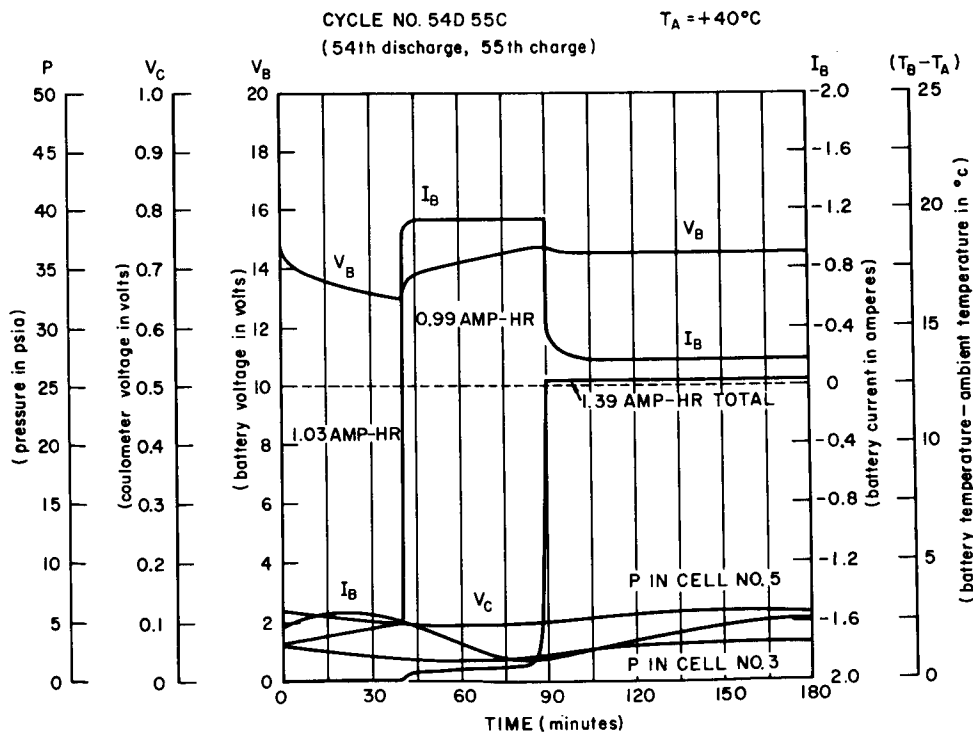


Figure 15—RAE Battery Test No. T2/CLM/101 (+40), Cycle
No. 54D 55C (54th discharge, 55th charge)

Crane points out the severe life penalty suffered in nickel-cadmium operations at 40°C. There is every reason to believe that the cadmium-cadmium cell will behave likewise since it is made of the same materials. The recommended temperature range is 0°C to 25°C with any needed increase in the range of thermal excursions to be permitted only on the lower end.

Coulometer testing is continuing at NAD Crane on behalf of NASA and the space industry.